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Fiber Reinforced High Performance Concrete for Special Applications

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Abstract. The paper refers to the experimental works being carried out within the research of special concrete precast elements of civilian infrastructure, which exhibit improved mechanical performance when exposed to the explosion.

The experimental work is aimed at designing the concrete mixtures for special applications such as trash bins and baggage lockers, in which several types of aggregate and reinforcement are used. The effects of aggregate types and sizes and types of reinforcement (oriented and randomly dispersed) are presented. The reinforcements used are various metallic and non-metallic nets and dispersed fibers. Mechanical and explosion tests were performed and the effect of different kinds of aggregate and reinforcement on explosion resistance and mechanical performance of the concrete samples were evaluated.

For lower explosion load levels the reinforced high performance concrete is a good and mainly inexpensive solution compared to recently applied other system.

1 Research significance

The high performance concrete itself as a quasi-brittle material does not conform to the resistance requirements, as at the explosion many secondary fragments are formed while the concrete breaks. The additional reinforcement (planar or randomly dispersed) provides the supporting 2D or 3D network within the concrete structure and thus increases the performance significantly.

For the investigation of explosion resistance of concrete elements the effect of concrete composition and mainly of different types of aggregate was observed in the first stage. Next the reinforcement (planar and dispersed) was introduced and the improved explosion resistance was evaluated.

2 Experimental invetigation

Concrete mixtures of various compositions and reinforcement were prepared. For the mechanical performance investigation the cube 150 mm [5.91 in.] and prism 100x100x400 mm [3.94x3.94x15.75 in.] specimens were made and the bulk density according to ČSN ISO 6275, compressive strength and flexural strength at 28 days of age in accordance with ČSN EN 12390-3, 5 were measured.

Specimens of selected mixtures, sized 80x80x480 mm [3.15x3.15x18.9 in.], were notched and subjected to fracture characteristics determination tests. The notch is made in 220 mm [8.66 in.] of specimen's span, into 1/3 of the specimen width; the width of the notch itself is approx. 2 mm [0.08 in.]. The parameters such as modulus of rupture, modulus of elasticity, effective crack length and fracture toughness are determined in accordance with the effective crack model methodology developed by Karihaloo and Nallathambi [1]. This method determines the fracture toughness of plain concrete from three-point load specimens which accounts for the pre-peak crack growth that occurs upon loading. The fracture toughness so determined is shown not to depend on the size and geometry of the test specimen but on the mix variables only. The regression equations presented for determining the effective notch depth are very accurate as they are based on an analysis of not only the authors' test data but that of several researchers around the world. They are shown not to depend on the size and geometry of test specimens. In fact, although these expressions were developed using three-point load data, it is shown that they may be applicable to four-point load specimens too. It is also shown that the predictions of the effective crack model are in good agreement with two non-linear models namely, the two parameter model and the size effect law [1, 2].

The result of the fracture determination test is a working diagram (load-deflection diagram). The values of load and deflection referring to the linear part of a curve are and to the peak maximum of a curve are taken and applied next for calculation of modulus of elasticity, effective crack length and fracture toughness. Also the next parameter – modulus of rupture appeared to be useful to determine. It is defined as the flexural strength assessed on the notched beam. It depicts the sensitivity to the notch and as the sample diameters are the same, it gives a good view into the sensitivity changes. It is one of the most sensitive and at the same time easily measurable indicators of changes in the microstructure of concrete, particularly of changes in the micro-cracks development [2].

For the explosion tests the concrete boards 40x500x500 mm [1.57x19.69x19.69 in.] were produced and a developed test procedure was applied. It consists in measuring the vibrations and further acceleration of the test stand holding the sample, which is subjected to the explosion load. The concrete specimen is fixed in the steel frame of the stand and the stand is placed on the sand foundation. The cylinders of Semtex 1A plastic high explosive weighting 100.0 g [0.220 oz.] and having the dimensions d = 45 mm [1.77 in.], h = 45 mm [1.77 in.] are used as testing charge.

Fig. 1 Test stand

The acceleration detector is attached to the steel frame of the stand - the data from the acceleration sensors is collected for at last 500 milliseconds using sampling frequency of 200 kHz. The acoustic detector of explosion is used for triggering the data collection. The results of the measurements are data characterizing the material capability of absorbing the blast energy. The obtained data are processed and the absolute value of acceleration is gained which is then integrated.

The integrated value enables to compare the energy absorbed by particular materials – the lower the integral value, the more blast energy was absorbed by the specimen. The energy absorption is one of the parameters – however the integrity of the sample must also be taken into consideration when evaluating the overall sample blast resistance performance. Hence the comparison of the samples is done using the following equation: 1/(Relative attenuation*Integrity), where Integrity value reflects the integrity of the sample after subjected to the blast load – the integrity was marked using number from 1 (the sample is without visually noticeable changes after blast load) to 5 (the sample is broken to small pieces after blast load). The outputs of the equation given above are shown in Fig. 9 and were used to compare the overall performance of samples when subjected to the blast load – the higher value means better overall blast resistance of the sample (combination of the absorbed energy and preservation of the sample integrity).

3 Figures and tables

Mechanical parameters (compressive and flexural strengths) and specific densities of prepared concrete samples are summarized in Figs 2, 3 and 4 respectively.

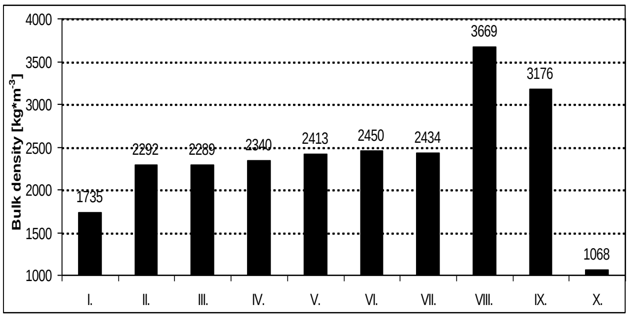

Fig. 2 Bulk density of prepared concrete specimens

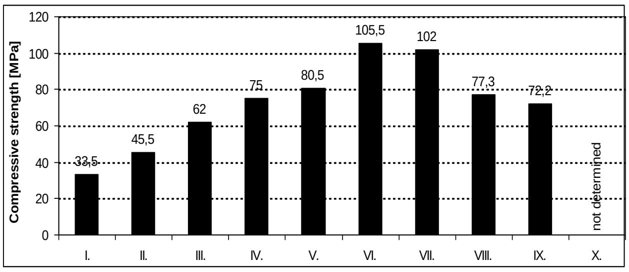

Fig. 3 Compressive strength of prepared concrete specimens

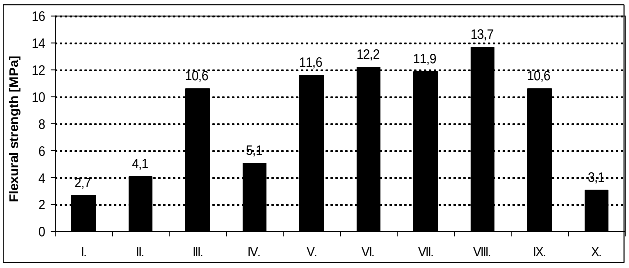

Fig. 4 Flexural strength of prepared concrete specimens

Only selected concrete specimens (No. I through No. VII) were subjected to the fracture parameters (modulus of rupture, modulus of elasticity, effective crack length and fracture toughness) assessments. However, when measuring the fracture characteristics on the reinforced concrete, some inaccuracies must be expected, as recent knowledge does not provide the accurate fracture model, which would give objective values measured on relatively small reinforced specimens.

The curves of especially reinforced concretes do not exhibit the linear progression. Usually the peak maximum values are difficult to define, thus must be considered as only benchmarks. Nevertheless, as the samples are of the same diameters and shapes and the procedure conditions do not change, the values can be well used for comparative evaluations. The fracture characteristics calculated from obtained curves are shown in Figs. 5 through 8.

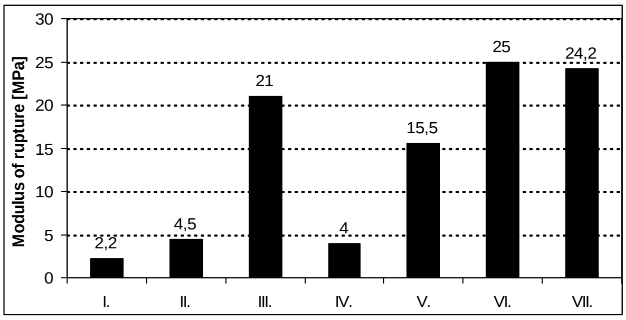

Fig. 5 Modulus of rupture of concrete specimens

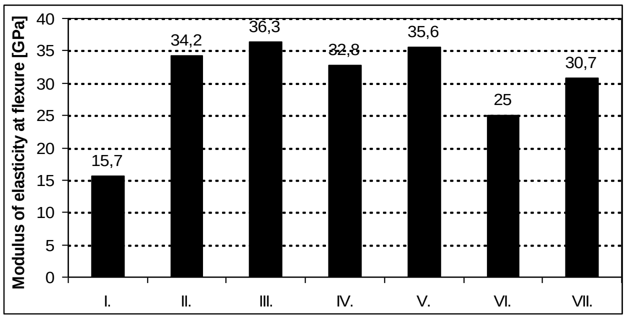

Fig. 6 Modulus of elasticity at flexure of concrete specimens

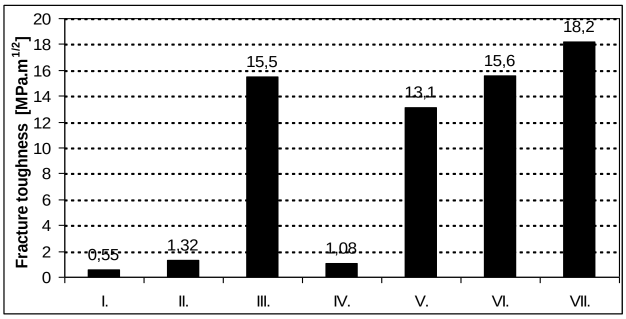

Fig. 7 Fracture toughness of concrete specimens

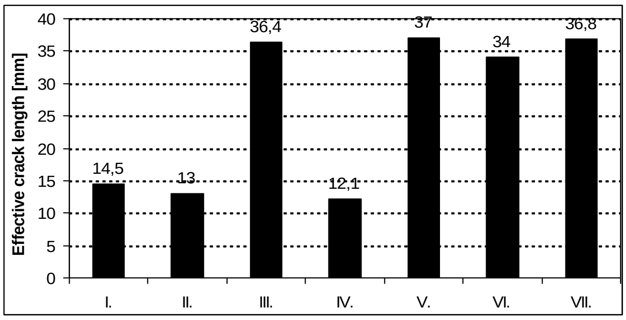

Fig. 8 Effective crack length of concrete specimens

The acceleration signals were recorded at the explosion tests and after processing the data the explosion resistance of the samples expressed as the 1/Relative attenuation*Integrity ratio was compared to the resistance of Dural (aluminum alloy) standard. The results are summarized in Fig. 9.

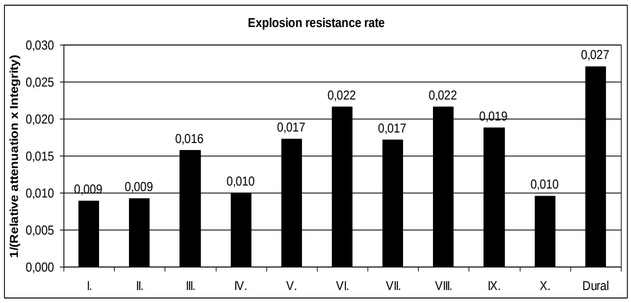

Fig. 9 Explosion resistance of concrete specimens

4 Discussion

To develop the material suitable for the blast protection applications, the special concrete systems were prepared with various kinds of reinforcement. The explosion resistance was determined and confronted with such material characteristics as mechanical performance and fracture parameters. The results were evaluated from four different points of view: the effect of 1) binder content, 2) presence of admixture, 3) aggregate type and 4) kind of used reinforcement was observed.

1) The binder content: The effect due increased binder content can be defined when the sample No. II (cement CEM I 42.5R 327 kg/m3 [326.6 oz/ft3]) and No. IV (cement CEM I 42.5R 465 kg/m3 [464.5 oz/ft3]) and samples with dispersed reinforcing steel fibers No. III (cement CEM I 42.5R 305 kg/m3 [304.6 oz/ft3]) and No. V (cement CEM I 42.5R 443 kg/m3 [442.5 oz/ft3]) are compared. As expected, the compressive strengths are influenced the most; the flexural strengths are not affected in such a significant degree. The fracture characteristics showed lower values at increased cement content and the explosion resistance was not influenced by the cement content.

2) The presence of admixture: As for the admixture (microsilica) presence (compare sample No. V – no admixture to sample No. VI – microsilica 37 kg/m3 [37 oz/ft3]; both reinforced with dispersed steel fibers), the same facts can be claimed regarding the mechanical parameters as for cement content findings. However, the fracture parameters were much more affected. The modulus of rupture and the fracture toughness were higher in samples containing microsilica, the modulus of elasticity was lower and the effective crack length was smaller. Regarding the explosion resistance, the sample containing microsilica (No. VI) showed considerably better performance compared to the sample with no admixture (No. V).

3) The type of aggregate: For the evaluation of the effect of aggregate type the sample No. I (lightweight coarse aggregate) and No. IV (coarse aggregate – quartz) and samples reinforced with micro-steel fibers and 2 plies of steel lathing (net), No. VIII (fine aggregate – sand, coarse aggregate – ferrosilicium) and No. IX (fine aggregate – sand partially replaced by fine ferrosilicium, coarse aggregate – ferrosilicium) were considered. It can be assumed that the higher the content of the aggregate with high performance characteristics, the higher the

mechanical parameters and the better the explosion resistance.

4) kind of reinforcement: The effect of reinforcement was evaluated comparing the sample No. II (not reinforced) to sample No. III (dispersed steel fibers; length 60 mm [2.36 in.]) and sample No. VI (dispersed steel fibers, length 60 mm [2.36 in.]) to samples No. VII (decreased content of dispersed steel fibers, length 60 mm [2.36 in.]), No. VIII and No. IX (containing steel fibers 6 mm [0.24 in.] long and 2 plies of steel lathing). Generally the reinforcement by steel fibers brings the most effective contribution in the improvement of performance parameters and explosion resistance of all considered aspects. The reinforcement by steel lathing (nets) brought the best flexural strength, satisfactory compressive strength and explosion resistance, however many secondary fragments were formed as the concrete spalled off the steel layer at the explosion.

5 Conclusion

Based on the results of this experimental investigation, the following conclusions are drawn:

- Increased cement content in the concrete matrix did not bring significant improvements in performance characteristics besides higher compressive strength.
- The addition of microsilica into the system brought about much stronger stiffening effect; particularly in fracture characteristics, also excellent explosion resistance was achieved.
- As for the aggregate effect, the following conclusions can be made: the higher the content of the aggregate with high performance characteristics, the higher the mechanical parameters and the better the explosion resistance
- The best results of mechanical, fracture and explosion resistance parameters as well were obtained with samples containing dispersed reinforcing steel fibers, the steel lathing (planar) reinforcement showed satisfactory mechanical performance and also as for the blast energy absorbance the samples performed very well, however many secondary fragments were formed as the concrete spalled off the steel lathing at the explosion and so the integrity was poor.
- As good absorption of the blast energy by soft expanded materials such as Styrofoam was expected, the sandwich system of concrete reinforced by dispersed glass fibers containing the polystyrene core of the thickness of 20 mm [0.79 in.] (sample No. X) was produced and subjected to flexural strength determination and explosion resistance assessing procedures. Despite good blast energy absorption, the integrity of the sample and thus also the overall explosion resistance was rather poor.

As can be seen from the conclusions made, the improved mechanical performance (particularly flexural strength, compressive strength not in such degree) together with improved fracture performance caused by the reinforcement brought about improved explosion resistance as well. Hence the drift in the development of the blast protection concrete materials from brittle-like to the ductile ones is being followed.

Acknowledgment

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References

[1] KARIHALOO B.L., NALLATHAMBI P., Effective crack model for the determination of fracture toughness (K_{Ic}^e) of concrete, *Engineering Fracture Mechanics,* V. 35, No. 4-5, 1990, pp 637-645.
[2] SCHMID P., BÍLEK V., KERŠNER Z.: Lomové parametry betonu a jejich zjišťování“, *Conference Proceedings Betonářské dny* 1998, pp. 266 – 271.